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Soil Moisture Response to a Changing Climate in Arctic Regions (Extended Abstract)

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1. Introduction

Soil moisture is the land surface hydrologic variable that most strongly affects land-atmosphere moisture and energy fluxes. In Arctic regions, these interactions are enhanced by the role of permafrost. Especially in northern regions, soil moisture therefore is important not only as a hydrological storage component, also as a result of its strong influence on the hydrological cycle through controls on energy fluxes such as evaporative heat flux, phase change in freezing or thawing of wet soil, and effects on thermal conductivity. With projected increases in surface temperature and decreases in surface moisture levels that may be associated with global warming, it is likely that the active layer (the near-surface layer of soil that experiences seasonal freezing and thawing) thickness will increase, leading to subtle but predictable ecosystem responses such as vegetation changes. Field measurements of soil moisture have been collected on the North Slope of Alaska, with emphasis upon establishing macro and micro-topographic influences. Sites were installed in the foothill regions and on the coastal plain of the Kuparuk River basin. Preliminary results indicate macro-topographic gradients greatly impact the importance of lateral versus vertical fluxes. Micro-topographic differences affect the small spatial scale differences in soil moisture, but have less impact upon flux direction. Soil moisture dynamics are controlled primarily by recent weather, topographic position, and presence or absence of permafrost; however, it is also markedly impacted by temperature (Luthin and Guyman, 1974) and soil type.

Discussion

Permafrost in arctic regions exerts a significant influence on soil moisture through controls on vegetation and drainage. In relatively flat areas where the ice-rich frozen layer is near the surface, the soil moisture contents are usually quite high. These areas have relatively high evapotranspiration and sensible heat transfer, but quite low conductive heat transfers due to the insulative properties of thick organic soils. As in more temperate regions, watershed morphology exerts strong controls on hydrological processes; however unique to arctic watersheds are complications arising from the short-term active layer dynamics and longer-term permafrost dynamics. As the active layer becomes thicker throughout the summer, it has a greater potential capacity to store water, resulting in a time-varying basin response to storm events. As the season progresses, the stream recession rates increase as more hillslope water flows through the soil rather than as overland flow. Peak flows are also more attenuated as the active layer increases in thickness or as permafrost areal extent decreases (Bolton *et al.*, 2000).

Thermokarst formation leads to very high soil moistures in the bottom of the thermokarst and a subtle drying along the banks of the thermokarst. This subtle drying along the banks may be the impetus for shrub invasion. In response to some disturbance, such as a tundra fire or perhaps climatic warming, segregated ice in permafrost may differentially thaw, creating irregular surface topography. Depressions forming on the surface soon form ponds, accelerating subsurface thaw through lower albedo and additional heat advected into the pond through runoff. In time a talik (a layer of unfrozen soil above the permafrost and below the seasonally frozen soil) may form below such ponds as the depth of water becomes greater than the amount that can refreeze during the winter. If the talik grows to a size that completely penetrates the underlying soil or connects to a subsurface layer that allows continued drainage, the pond may then began to drain or be replenished from subpermafrost groundwater.

Understanding ecosystem response to degradation of permafrost is an important research question and one that has no single answer. The rate of permafrost thawing, the amount of ground surface subsidence, and how the hydrologic regime responds to permafrost degradation all depend on numerous site characteristics including thickness of organic soil, amount of subsurface massive ice and local terrain. In some cases, the surficial soil may become drier when subsurface drainage improves as pores formerly plugged with ice become free to transmit water. In wetlands that are groundwater

Fig. 1. Prior to thermokarsting, this was an area of relatively homogeneous tussock tundra ; now it has aquatic sedges in the growing in the saturated bottom and shrubs (Betula nana and Salix) are developing along the steep banks, in zones of depleted soil moisture.

discharge zones, permafrost degradation accompanies subsidence of the surface and inundation with water. Disturbance to the arctic tundra will increase the depth of thaw for many years following the disturbance. This can cause extensive thermokarsting, heterogeneous drying of surface soils and a change in dominant vegetation types. Such disturbances include changes in drainage patterns, increasing dust deposition and climate warming. Thermokarst formation leads to very high soil moistures in the bottom of the thermokarst and can cause drastic drying at the surface of the adjacent land, resulting in a shift of vegetation type (Figure 1).

The presence or absence of ice-rich permafrost exerts the dominant controlling influence on hydrologic processes in northern boreal forests, allowing or preventing infiltration to subsurface groundwater. Soils over ice-rich permafrost tend to be wetter with thicker organic mats as compared to soils in permafrost free areas. This impacts most biological and physical processes occurring in the boreal forest. The depth to which the active layer will thaw each summer season depends upon many local factors, especially site hydrology. Other seasonal factors that influence depth of thaw include temperature and levels of soil moisture due to variation in precipitation and evapotranspiration. The inter-annual variation of thaw depth at a site is quite large and consequently, utilizing depth of thaw as an indicator of climatic change may be quite difficult ; however, the deeper permafrost acts an integrator of meteorological variations and will respond to long term changes in climate. As the active layer thickens in response to a warming climate, it may reach the point where it does not re-freeze in the winter, forming a talik. At this point, soils may be able to drain continuously throughout the year, draining ponds and drying surface soils.

The number of wildfires in North America is increasing (Kasischke and Stocks, 2000). Consistent data on changing fire return period, severity or recovery patterns is not available. Fires cause a short-term increase, but a long-term decrease in near surface soil moisture. After fire, albedo declines to about-0.04, resulting in an increase in shortwave input and surface temperature increases substantially. The loss of the canopy during the fire results in a much less efficient convection of heat and moisture from the surface. The high surface temperature results in high long-wave radiation from the ecosystem to the atmosphere, which approximately balances the shortwave radiation input. Consequently net radiation actually decreases following fire, despite the lower albedo (Yoshikawa *et al.*, 2003). Meanwhile, transpiration decreases, but evaporation increases. Degradation of the permafrost, whether in response to a warming climate or fires, will cause marked changes to surface soil moisture levels. Four years after a wildfire in the boreal forest, soil temperatures were higher and soil moisture was greater in the burned area compared to a comparable non-burned site (Figure 2a). This was due to darker surface and lower rates of transpiration. Ten years after a fire, the soils of the burned area were drier (Figure 2b) as the active layer became thicker and internal drainage improved. The soil moisture regime is influenced by wildfires, but it also has a strong influence upon probability of wildfire initiation. As the climate changes, the fire frequency will also change.

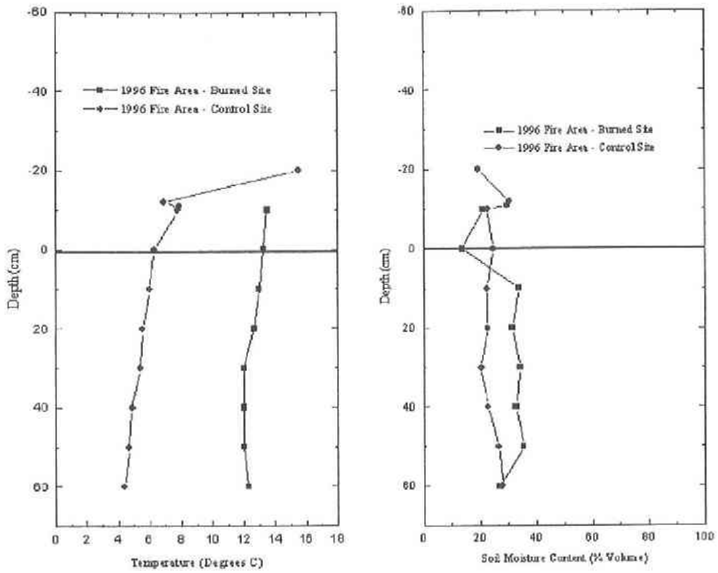

Fig. 2a. Soil moisture and temperature data collected in comparable burned and control sites four years after the fire demonstrate that the burned area is warmer and wetter than the control site. These differences are due to lower albedo and lower transpiration in the burned area.

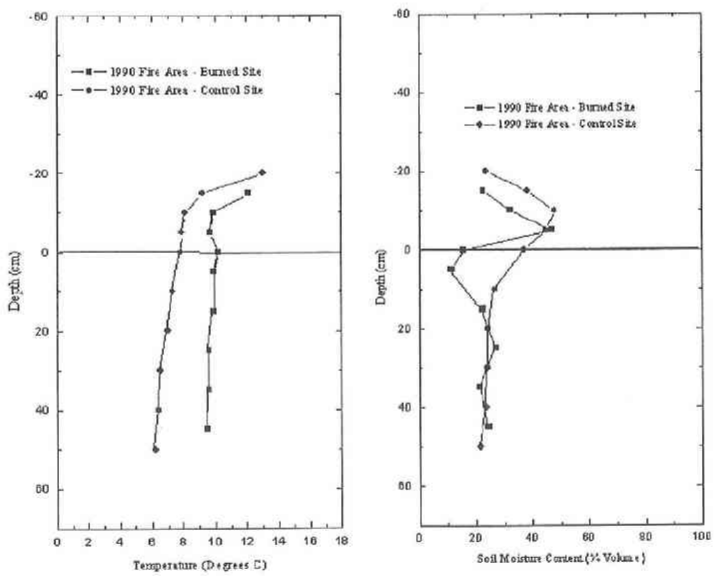

Fig. 2b. Soil moisture and temperature data collected in comparable burned and control sites ten years after the fire demonstrate that although the burned area is still warmer than the control site, moisture levels are nearly the same.

The immediate impacts to moderate fires include killing of the vegetation, and increasing soil moisture and temperature. In cases of more severe fires, the surface organic layer is entirely combusted exposing the mineral soil beneath. Any disturbance to the surface layer will increase heat flow through the active layer into the permafrost. After approximately three to five years (depending upon site conditions) the active layer will increase to a thickness that does not completely refreeze the following winter forming a talik. Several decades later, thermokarst form caused by the thawing of the ice-rich permafrost. The thicker talik and vegetation recovery (higher albedo and transpiration) will make the ground surface drier. This represents a "turning point" in the soil moisture regime. At this time, soils can continually drain throughout the winter and the active layer soils become progressively drier.

Conclusions

Soil moisture is markedly impacted by permafrost distribution and it also exerts a controlling influence upon surface ecology and climatic processes. As permafrost distribution or active layer thickness changes, soil moisture will proceed through simultaneous changes. Soil moisture may progress through dramatic or threshold changes as the permafrost degrades to the point of allowing soil moisture to drain internally, particularly if the active layer does not completely freeze during the winter. Wildfires initiate substantial changes in surface soil moisture levels. These changes can be evident over large areas and long time periods and thus can feedback to impacting local and regional climate.

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